ARTICLE

Evolution of Students' Ideas About Natural Selection Through a Constructivist Framework

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The concept of biological evolution within populations, or genetic change over time to populations, is a central principle of biological science; "Nothing in biology makes sense except in the light of evolution" (Dobzhansky, 1973). However, national polls show that over 45% of Americans do not accept the theory of evolution by natural selection (Quammen, 2004). Moreover, in the debate about whether or not evolution should be taught in schools, we have lost sight of what students really understand about the process of natural selection and its role in evolution.

Educating students about the process of evolution through natural selection is vitally important because not only is it the unifying theory of biological science, it is also widely regarded as difficult for students to fully comprehend (Sandoval, 2003). Anderson and colleagues (2002) describe alternative ideas and misconceptions about natural selection as highly resistant to change. Catley (2006) suggests that the educational emphasis on microevolutionary processes has left both teachers and students with a poor understanding of macroevolution and speciation.

To truly understand evolution, students need to understand other basic biological processes. Educational literature confirms that comprehension of evolution is made possible through the understanding of the individual concepts that comprise the theory (Passmore & Stewart, 2000). Even when students do grasp the basic idea of natural selection, the underlying concepts may be unclear (Kadury-Slezak, 2001). Many students also tend to view individual organisms as representative of entire populations and fail to recognize population variation as necessary for evolutionary change; thus students do not distinguish between individuals and species when describing selection (Greene, 1990; Halldén, 1988). Such typological thinking can lead to a belief that organisms have the power to change their traits in response to the environment, particularly when students fail to understand mechanisms of inheritance (Heim, 2002; Sandoval, 2003; Wood-Robinson, 1995).

Compounding the problem is that in many courses of study, students' experience with science is merely a survey of information without any meaningful exposure to the process that produced the information (Clough & Olson, 2004). This missing component of science education is evident in the public's lack of understanding about what constitutes a scientific theory (McComas, 2004). In science, a theory is an explanation based upon extensive testing that is well-supported by the accumulation of evidence. When students are not exposed to studies in the nature of science, they are not able to distinguish between a scientific theory and the vernacular usage of theory to mean a guess or an unsupported explanation (Backhus, 2004). This discrepancy between a scientific theory and a personal theory is of particular relevance to evolution education because one of the common misconceptions about evolution is that it is "just a theory."

Instruction that highlights the nature of scientific thought is the key to students' understanding about natural selection. Instruction in evolution must therefore focus also on the epistemic thinking that has led to the development of evolution theory as the best scientific explanation we have for the diversity of life on Earth. According to Sandoval (2003) such instruction should include scientific epistemological components like causal explanations, parsimony in developing conclusions, accounting for observations in explanations, and reliance on creativity. If students have a basic knowledge of the nature of science, their development of explanatory models can actually reconstruct the concept of natural selection (Passmore & Stewart, 2000). Conceptualization of the scientific process also helps students understand why scientists consider natural selection to be a strongly-supported theory and the best explanation for life's diversity (Backhus, 2004).

The challenge to teaching concepts such as natural selection through the process of inquiry is that oftentimes student beliefs drive the direction of the inquiry (Sandoval & Morrison, 2003) whereas the goal of instruction may be conceptual change of those beliefs. The gradual addition of new knowledge can help steer the inquiry while crafting new concepts or changing existing misconceptions. Strategies for conceptual change include active engagement with evidence, consideration of student learning needs, representation of the nature of science within the concepts under study, and a challenging curriculum (Tytler, 2002). These strategies reflect the practice of scientific investigation itself and can be particularly powerful for a complex concept such as natural selection. Geraedts and Boersma (2006) found that when students were engaged in guided reinvention of the development of Darwin's theory through a sequence of questions based on the logical nature of the theory, the majority of students developed Darwinian concepts of change over time.

A constructivist model provides a framework for effective teaching about natural selection by progressively adding concepts into the framework of existing knowledge. This model of instruction is particularly useful when the theory is used as an organizing principle for constructivist teaching and is presented as a framework for further investigation rather than an indisputable fact (Andersson & Wallin, 2006; Sandoval & Reiser, 2004). Cladistic analysis and

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other analytical tools used to reconstruct relationships and understand evolutionary history can also be powerful cognitive aids in promoting students' understanding of speciation (Catley, 2006).

Constructivist philosophy involves building new concepts into the ideas and beliefs already held by students. Constructivist learning represents the assimilation of new ideas into existing worldviews and the shifting of those worldviews to accommodate the new ideas (Brooks & Brooks, 1993). Teachers who use constructivism develop lessons that take students' previous conceptions into account and build new knowledge sequentially. Constructivist lessons account for both previous and upcoming content, and each lesson or idea builds upon previous ones. Constructivist teachers provide opportunities for students to collaborate and discuss ideas with one another, as such discussions are recognized as necessary for assimilation and accommodation. Constructivist learning thus involves a building of knowledge upon the foundation of concrete experiences both inside the classroom and in students' everyday experience.

In order to effectively develop curriculum for the teaching of evolutionary biology, it is important to know what students think and understand about natural selection. For this study, we surveyed 9th grade (freshman) general science and 12th grade (senior) biology students' knowledge and attitudes about natural selection before and after a constructivist sequence targeting specific concepts related to natural selection and the nature of scientific investigation. Our goal was to investigate whether students grasped not only the basic theory of natural selection, but also the underlying concepts that support the theory and are needed for a more thorough understanding of natural selection. We identified these fundamental concepts as (1) population variation, (2) mutation and the genetic basis for diversity, and (3) selective pressure in the environment.

Table 1. Constructivist activities used to teach natural selection.

CONCEPT	ACTIVITY	CONSTRUCTIVIST CONNECTIONS
Taxonomy Common ancestry	Students classify different organisms and highlight the unique features held in common at each level.	Builds toward: Elicits question, *Why are there so many kinds of organisms?* Highlights features that demonstrate points of divergence and common ancestry.
Genetic basis of inheritance Mutation	Students model transcription errors through "telephone" game. Recording the message meaning at various points in chain illustrates change through additive mutations. Student "mutagens" purposefully change message.	Builds on: Demonstrates mechanism for change and diversity. Builds toward: Foundation for microevolution model by providing mechanism for antibiotic resistance.
Microevolution Population variation Random process	Students model microevolution in a population of "bacteria" (colored paper clips). Dice rolls simulate variable probability of death in wild type and resistant bacteria. Students graph simulated population dynamics of both types through multiple courses of antibiotics.	Builds on: Demonstrates change in population structure following mutation. Builds toward: Introduces idea of selective pressure and how traits are selected for or against.
Selective pressure on populations	Student "predators" hunt for red bean and split pea "prey" in a rice environment using chopsticks. Students graph populations of small, hidden peas to large visible beans over multiple generations. Students repeat activity with black and white beans in white or wild (black) rice environments.	Builds on: Demonstrates how selective pressure operates when one feature increases likelihood of survival to reproduction in the environment of the organism. Builds toward: Population variation can lead to speciation when selective pressures in different environments lead to selection for different traits.
Speciation Adaptive radiation	Students match marsupials and placentals to identify how selective pressure can modify ancestral type to fill a range of niches. Students make adaptations to styrofoam ball "ancestral type" organism for different environments. Multiple students adapt organisms in same environment to demonstrate random nature of mutation and diversity of adaptations to same habitat.	Builds on: Examination of evidence to support how can selection for traits in different environments can lead to diversity of organisms. Reinforcement of genetic inheritance through demonstration of similar selective forces on marsupials and placentals. Modeling adaptive radiation from a common ancestor to diversity of species depending on random mutation and environmental pressures.

○ Methods

The Students

This study was conducted at the University Laboratory School (ULS) in Honolulu, Hawaii, which is a charter school and test ground for curriculum at the University of Hawaii's Curriculum Research and Development Group (CRDG). The ULS student population is selected by stratified lottery to represent a cross-section of the state's educational population. Thus, a range of ethnicities, socioeconomic groups, and ability levels are included in heterogeneous ULS classes. All students take the same curriculum and share a common educational background with their peers once they enter the school. We took advantage of a change in teaching staff and curriculum that provided a unique opportunity to compare the attitudes of seniors and freshmen who had not been previously exposed to formal instruction about evolution. We worked with freshmen in the Marine Science course (a general science course) and seniors in the Biology course. Each course was divided into two classes. The freshman course contained 52 students of equal sex distribution. The senior class contained 49 students. Because the senior class had a high level of absenteeism due to college visits, we were only able to collect data from 39 seniors (17 males and 22 females).

Students enter ULS in kindergarten, 6th, or 8th grade. The high school science course sequence from 9th to 12th grade is: Marine (General) Science, Physics, Chemistry, and Biology. ULS students who had taken Marine Science prior to the development of the natural selection unit described here had received lessons on classification and diversity without any explicit instruction in natural selection or evolutionary biology during their Marine Science experience. Thus, although the senior class in this study had taken more science courses, it had not previously received formal instruction on natural selection prior to the lessons presented during this study.

Instruction

After completing a pre-survey (described later), students took part in a constructivist unit on natural selection. Each lesson emphasized an aspect of natural selection theory and built upon the previous lessons. We did not develop this sequence to lead students through Darwin's reasoning as in some other evolutionary biology sequences (Geraedts & Boersma, 2006). Rather, we attempted to build a logical sequence of lessons and activities that provided for an increasingly complex and inclusive idea of natural selection as a mechanism for genetic change within populations over time.

The lesson sequence introduced concepts through laboratory activities, models, and simulations (Table 1). In alignment with constructivist learning philosophy, each lesson not only built on previous concepts but also connected to upcoming lessons. The laboratory activities were not used to demonstrate concepts that had already been introduced, but rather to elicit student questions that would lead to the discovery of those concepts. The simulations were designed to produce variable results and provide room for student interpretation and discussion about what their data meant. The simulations also provided concrete models that students could manipulate and experience directly. These simulations, which students could directly experience, were connected to real-world examples that students could not see directly in action. We emphasized the use of evidence to produce patterns and draw conclusions. Through the use of a constructivist strategy, in each new segment of the unit we emphasized continual building of evidence and application of knowledge learned in previous lessons. Readers of Darwin know that he approached the building of his theory in the same way.

Although both the freshman and senior level courses utilized the same basic sequence of lessons, we did make modifications to the sequence in response to student questions and to align to the curricular program. For example, in Marine Science, the unit was connected to a previous unit on fish diversity, and fish served as the prime example of natural selection in action. In Biology, a heavier emphasis was placed on the genetic aspects of the theory in connection to the course material on genetics.

The Surveys

Students were given surveys prior to and following the unit. The surveys were designed to gain information about students' understanding of natural selection processes as well as their attitudes about the theory (Appendix A). These surveys were administered to students anonymously, with each student given an alphanumeric code to enable paired comparisons of pre- and post-surveys.

The surveys consisted of three parts. The first part asked students to list the first three words they thought of when considering natural selection. We categorized these words based on the type of word selected. These categories were positive, negative, misconcep-

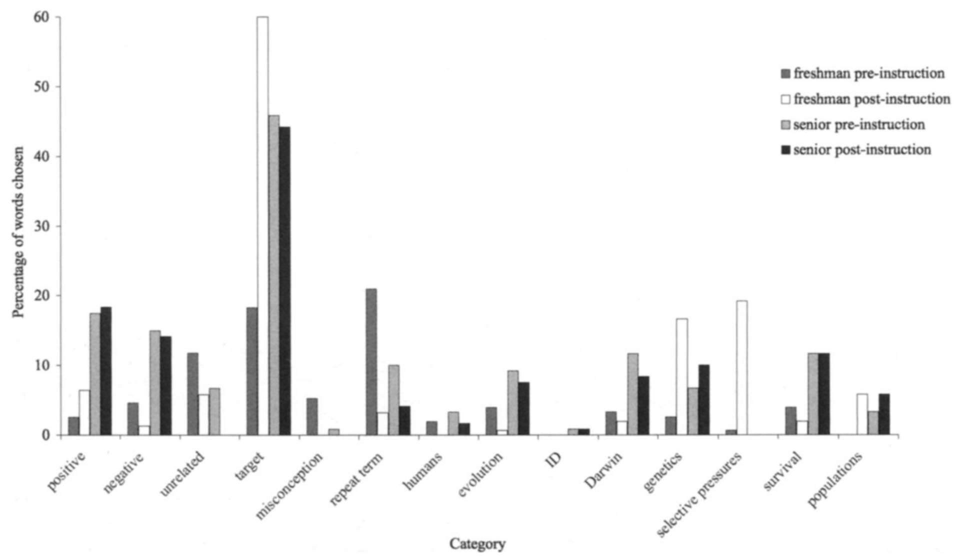

Figure 1. Percentage of word types recorded by freshmen and seniors before and after instruction. Note percentages total more than 100% due to overlap in categories (e.g., words like *populations* or *selective pressure* also represent target concepts).

Table 2. Differences in word choice within and between class before and after instruction. Differences were compared pre- and post-instruction using two-sample, paired *t*-tests within grade levels and unpaired *t*-tests between grade levels. Significance at $p \leq 0.05$. X refers to no selection of words in the category, eliminating the basis for statistical comparison.

Word Type	Statistical Value	Pre-Instruction Freshman-Senior Comparison	Post-Instruction Freshman-Senior Comparison	Freshman Pre-Post Instruction Comparison	Senior Pre-Post Instruction Comparison
Positive	Df	97	90	101	86
	t	-3.038	-2.690	-0.786	-7.050
	p	**0.002**	**0.004**	0.217	0.241
Negative	Df	97	90	101	86
	t	-2.412	-4.144	1.596	-0.389
	p	**0.009**	≤ 0.001	0.057	0.349
Unrelated	Df	97	90	101	86
	t	1.286	1.869	1.309	1.670
	p	0.101	**0.032**	0.097	**0.049**
Target	Df	97	90	101	86
	t	-3.339	2.235	-6.739	-0.863
	p	**≤ 0.001**	**0.014**	**≤ 0.001**	0.195
Misconception	Df	97	X	101	86
	t	1.798	X	2.24	0.912
	p	**0.037**	X	**0.014**	0.182
Repeat term	Df	97	90	101	86
	t	2.82	-0.436	4.756	1.23
	p	**0.003**	0.330	**≤ 0.001**	0.111
Humans	Df	97	90	101	86
	t	-0.47	-1.636	1.785	0.612
	p	0.319	0.052	**0.039**	0.271
Evolution	Df	97	90	101	86
	t	-1.471	-3.29	2.003	0.046
	p	0.072	**≤ 0.001**	**0.024**	0.481
Darwin	Df	97	90	101	86
	t	-2.496	-2.699	0.759	0.432
	p	**0.007**	**0.004**	0.224	0.333
Genetics	Df	97	90	101	86
	t	-1.14	1.56	-4.01	-1.322
	p	0.128	0.061	**≤ 0.001**	0.094
Selective pressures	Df	97	90	101	X
	t	0.970	3.808	-4.11	X
	p	0.167	**≤ 0.001**	**≤ 0.001**	X
Survival	Df	97	90	101	86
	t	-2.185	-3.810	1.072	-0.579
	p	**0.016**	**≤ 0.001**	1.429	0.282
Populations	Df	97	90	101	86
	t	-2.131	-0.023	-3.235	-1.292
	p	**0.018**	0.490	**≤ 0.001**	**0.010**

tion, unrelated concept, target concept, word repeat (use of nature or selection or some similar variation), humans, evolution, intelligent design, Darwin, genetics, selective pressure, survival, and populations. Because some words fit more than one category, we recorded the percentage of total words listed in each category. We compared word choice within both grade levels pre- and post-instruction using two-sample, paired *t*-tests, and we compared between grade levels both prior to and following instruction using two-sample, unpaired *t*-tests.

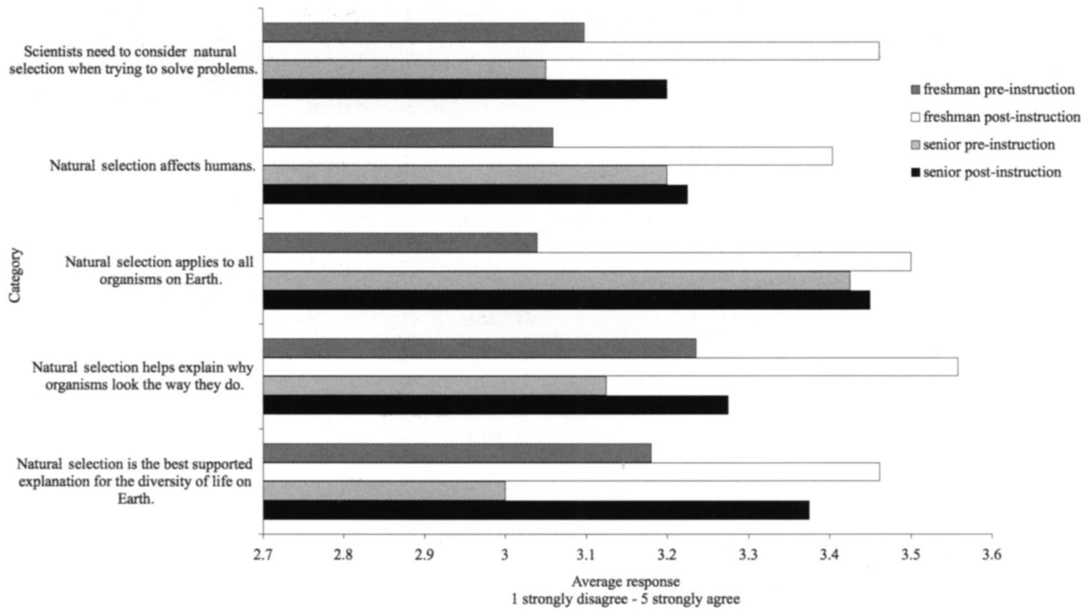

Figure 2. Attitude change in freshmen and seniors before and after instruction.

In the second portion of the survey we asked students to choose all correct responses to statements about natural selection. We recorded the number of students choosing each response and compared changes in both grade levels and between grade levels using binomial distributions to identify which answers were selected by students at levels above or below expected levels of 50% if students were randomly guessing at answers.

The final portion of the survey included a series of questions with Likert-scale responses to content and attitude statements about natural selection. We compiled the responses for each question and compared these via two-sample, paired *t*-tests for each grade level pre- and post-instruction as well as between grade levels both before and after instruction using two-sample, unpaired *t*-tests.

○ Results

Figure 1 shows the proportion of word types recorded by freshmen and seniors before and after instruction. Statistical analysis of word choices is summarized in Table 2. Prior to instruction, freshmen listed significantly fewer target concepts (18.3%) than did seniors (44.1%) in the word choice categories. Freshmen also listed significantly more words indicating misconceptions (5.2%) than the seniors (0.8%). Prior to instruction, the highest proportion of words recorded by freshmen were terms that repeated the idea of natural selection (20.9%), again at levels significantly higher than such terms were recorded by the seniors. For example, many freshmen used the words *nature*, *natural*, and *selection*. Conversely, the seniors recorded more words like *evolution* and *Darwin* (8.2% and 11.7% respectively). The seniors also listed significantly more words that identified ideas like *survival* (11.7%) and *populations* (5.8%).

Following instruction, the freshmen showed significant changes in eight categories of words listed compared to their choices prior to instruction, whereas the seniors showed significant changes in only one category. The seniors decreased the number of unrelated concepts they listed from 6% to 0, but otherwise did not show significant change in their word choice after instruction. Despite the emphasis on genetics in the ULS biology course, the seniors did not show a significant increase in terms related to the genetic basis of inheritance. The freshmen significantly decreased the proportion of words they listed that were misconceptions to 0 or repeat terms to 4.2%, and they also significantly decreased the number of times they listed *evolution* (0.6%). The freshmen also significantly increased their listing of target words to 60% and of specific target words related to populations (5.8%), selective pressures (19.2%), and genetic inheritance (16.7%). Only one student, a senior, mentioned *intelligent design* in both the pre- and post-surveys.

Both grade levels changed their attitudes about natural selection following instruction, as seen in Figure 2. In the statistical analysis of the attitude portion of the surveys (Table 3), freshmen significantly improved their attitudes about natural selection in response to all five statements. The seniors showed significant improvement in only one, "Natural selection is the best supported explanation for the diversity of life on Earth," with an average Likert response change from 3.0 to 3.4. However, prior to instruction, the freshmen had a significantly lower average response to the statement "Natural selection applies to all organisms on Earth," (3.0) compared to the seniors (3.4). Following instruction, freshmen had a significantly higher response to the statements "Natural selection helps explain why organisms look the way they do," and "Scientists need to consider natural selection when trying to solve problems," both with an average response of 3.5 in comparison to the senior response of 3.3 and 3.2, respectively.

Table 4 summarizes the percentage of students selecting each possible response to statements about natural selection. The associated binomial distribution statistics indicate when student responses were at non-random levels that would be expected if students were not simply guessing. When we asked students to identify accurate ideas about natural selection, the "don't know" response by freshmen overall dropped significantly following instruction. Prior to instruction, an average of 33.3% of freshmen responded "don't know" to the three statements provided. After instruction, an average of 2% of freshmen responded "don't know." This category did not change for seniors, as only two of them selected it as an initial response for any of the three statements. For the statement, "Natural selection applies to ..." (Figure 3a) both groups increased in their response to the target answer of populations (29% for

Table 3. Attitude change in freshmen and seniors before and after instruction. Students' Likert-scale responses (1 = strongly disagree; 5 = strongly agree) were compared via paired two-sample *t*-tests within grade levels and via unpaired two-sample *t*-tests between grade levels. Significance at $p \leq 0.05$.

Statement	Statistical Value	Pre-Instruction Freshmen-Senior Comparison	Post-Instruction Freshmen-Senior Comparison	Freshman Pre-Post Instruction Comparison	Senior Pre-Post Instruction Comparison
Natural selection is the best supported explanation for the diversity of life on Earth.	average response change	-0.18	-0.09	0.28	0.38
	Df	88	90	101	78
	T	1.338	0.760	-2.770	-2.490
	P	0.092	0.224	**0.003**	**0.007**
Natural selection helps explain why organisms look the way they do.	Delta	-0.11	-0.28	0.32	0.15
	Df	89	90	101	78
	T	0.850	2.460	-2.906	-1.110
	P	0.199	**0.007**	**0.002**	0.13
Natural selection applies to all organisms on Earth.	average response change	0.39	-0.05	0.46	0.03
	Df	89	90	101	78
	T	-2.806	0.393	-3.766	-0.175
	P	**0.003**	0.347	**≤ 0.001**	0.430
Natural selection affects humans.	average response change	0.14	-0.18	0.35	0.02
	Df	89	90	101	78
	T	-1.007	1.485	-2.879	-0.176
	P	0.158	0.704	**0.002**	0.430
Scientists need to consider natural selection when trying to solve problems.	average response change	-0.05	-0.26	0.36	0.15
	Df	89	90	101	78
	T	0.338	2.344	-3.306	-1.011
	P	0.368	**0.011**	**≤ 0.001**	0.157

freshmen, 13% for seniors). For both groups, following instruction, the binomial distribution statistic was significant, indicating choice above levels associated with random guessing. The freshmen increased their selection of individuals as the unit on which natural selection operates by 9%, while the seniors decreased this selection by 7%. For the statement about the measure of success in nature (Figure 3b), the freshmen had a range of responses prior to instruction, but they significantly increased their choice of surviving offspring as the accurate response by 36% with an associated significant binomial statistic. There was no significant change for seniors in response to this statement. In response to the statement about the source of change in organisms (Figure 3c), both groups significantly increased their response of random mutation. Freshmen increased this choice by 45% and seniors by 25% and the associated binomial distribution statistics indicated a choice level significantly above what would be expected in a random guess. However, both groups also retained the misconception about an organism's ability to modify itself, indicating both before and after instruction that organisms can change by learning to modify their bodies. Before instruction, 52% of freshmen and 53% of seniors selected this option, and after instruction 46% of freshmen and 48% of seniors did so. The binomial distribution statistics for each of these values were not significant, and did not indicate a clear change in knowledge about this particular aspect of natural selection.

○ Discussion

Our results suggest that while the seniors had more time to gain information about natural selection, they also had more time to solidify their conceptions. Even though the seniors had not previously received explicit instruction in natural selection earlier in their high school career, it appears that they picked up many concepts along

Table 4. Responses to statements about NS selected by students before and after instruction. The % columns indicate the percentage of students choosing each response. The binary statistic indicates p values for tests of binomial distributions used to identify which answers were selected by students at levels above or below expected levels of 50% if students were randomly guessing at answers. Significance at p ≤0.05. * indicates ideas supported by NS theory.

Concept	Answers	% Freshmen Choosing Pre-Instruction (binary statistic)	% Freshmen Choosing Post-Instruction (binary statistic)	% Seniors Choosing Pre-Instruction (binary statistic)	% Seniors Choosing Post-Instruction (binary statistic)
Natural selection applies to:	individuals	16 **(≤ 0.001)**	25 **(≤ 0.001)**	45 (0.113)	38 **(0.046)**
	populations*	44 (0.079)	73 **(≤ 0.001)**	53 (0.113)	60 **(0.046)**
	everything but humans	02 **(≤ 0.001)**	0 **(≤ 0.001)**	10 **(≤ 0.001)**	3 **(≤ 0.001)**
	all organisms*	66 **(0.009)**	71 **(≤ 0.001)**	88 **(≤ 0.001)**	78 **(≤ 0.001)**
	nothing	0 **(≤ 0.001)**	0 **(≤ 0.001)**	0 **(≤ 0.001)**	0 **(≤ 0.001)**
	don't know	28 **(≤ 0.001)**	0 **(≤ 0.001)**	3 **(≤ 0.001)**	0 **(≤ 0.001)**
The measure of success in nature is:	age reached	20 **(≤ 0.001)**	6 **(≤ 0.001)**	35 **(0.027)**	28 **(0.003)**
	enemies killed	10 **(≤ 0.001)**	2 **(≤ 0.001)**	15 **(≤ 0.001)**	13 **(≤ 0.001)**
	mating opportunities	32 **(0.004)**	15 **(≤ 0.001)**	25 **(≤ 0.001)**	38 **(0.046)**
	surviving offspring*	58 (0.060)	96 **(≤ 0.001)**	85 **(<0.001)**	90 **(≤ 0.001)**
	food gathered	22 **(≤ 0.001)**	2 **(≤ 0.001)**	28 **(0.003)**	13 **(≤ 0.001)**
	don't know	42 (0.060)	2 **(≤ 0.001)**	13 **(≤ 0.001)**	3 **(≤ 0.001)**
Changes to organisms result from:	organisms learn to modify parts	52 (0.108)	46 0.102)	53 (0.113)	48 (0.125)
	random mutation*	30 **(0.002)**	75 **(≤ 0.001)**	50 (0.125)	75 **(0.004)**
	genetic material passed on*	36 **(0.016)**	48 (0.110)	53 (0.113)	85 **(≤ 0.001)**
	parts lost	12 **(≤ 0.001)**	10 **(≤ 0.001)**	10 **(≤ 0.001)**	8 **(≤ 0.001)**
	supernatural	8 **(≤ 0.001)**	2 **(≤ 0.001)**	13 **(≤ 0.001)**	8 **(≤ 0.001)**
	don't know	30 **(≤ 0.001)**	4 **(≤ 0.001)**	10 **(≤ 0.001)**	0 **(≤ 0.001)**

the way. The freshmen, in comparison, had larger percentages of changes in both their attitudes about natural selection and their content knowledge. Although the seniors began ahead of the freshmen, the surveyed level of content knowledge in the freshmen improved beyond the demonstrated level of the seniors following instruction. When we examined attitudes about natural selection in response to a series of statements, we found that seniors and freshmen had a mixed range of positive responses prior to instruction. Following instruction, however, the freshmen again consistently outstripped the seniors with higher levels of positive response to all statements about natural selection. Freshmen also decreased their listing of replacement words like *natural* and *selection* as well as their use of the general term *evolution* in favor of more specific ideas. This evidence supports the suggestion that, in order to avoid misconceptions and allow for full development of inquiry, natural selection should be taught as early in the high school progression as possible.

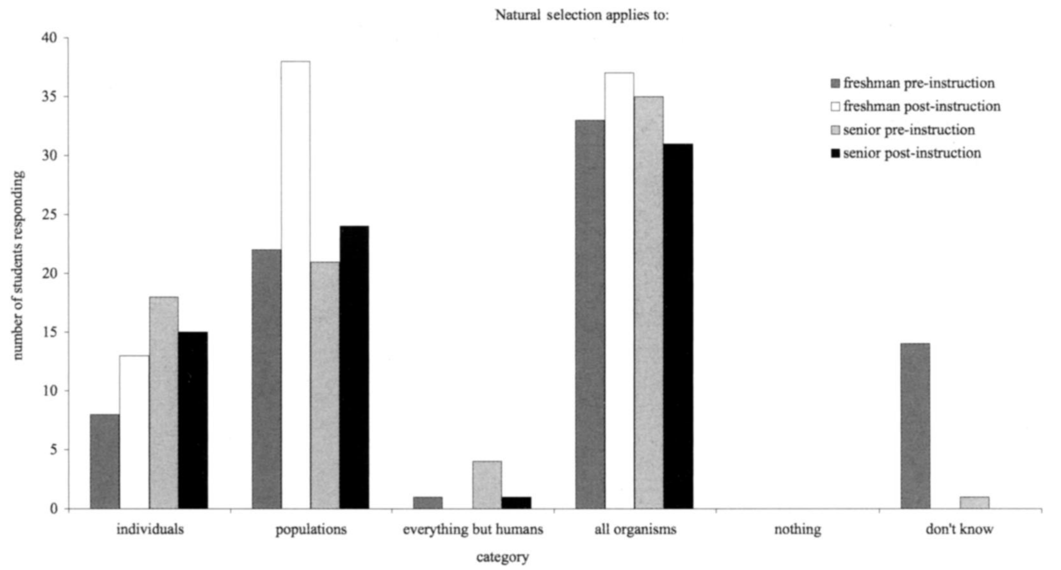

Figure 3a. Student responses to statement about groups influenced by natural selection before and after instruction rated on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree).

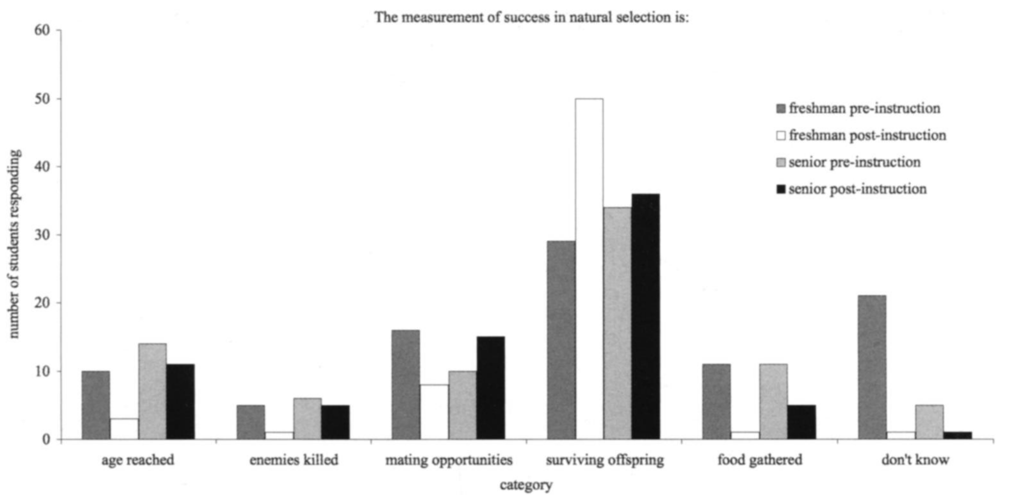

Figure 3b. Student responses to statement about measure of success in natural selection before and after instruction rated on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree).

One misconception identified and retained by both groups is that "Organisms learn to change their bodies over time." The number of students selecting this response did not change in either group after instruction. Although both freshmen and seniors increased their response to the accurate "random mutation" option, many were those students previously selecting "don't know." Thus, our data suggests that the students who entered into instruction with a Lamarckian idea of evolution retained it. Previous studies have found that students tend to view organisms conceptually as biological types that change directly in response to environmental pressure rather than through random mutation that introduces variation into the population of organisms (Shtulman, 2006; Wood-Robinson, 1995). The failure of students to change ideas about natural selection being the best-supported explanation for diversity may also be a result of student ideas about biological types.

The students' retention of the Lamarckian misconception highlights a gap in our sequence of instruction and identifies a missing link for students attempting to form a cohesive understanding of natural selection. One aspect of instruction that may be responsible for reinforcing Lamarckian misconceptions in students is that the freshman instructor placed continued emphasis upon species change in response to environmental pressures. This phrasing was used in part because the freshman unit focused on fish (whereas the senior unit focused on genes). This emphasis could have reinforced the idea that organisms do change their bodies purposefully in response to the environment, rather than the more accurate idea that the environment may select one change over another, but that change itself is solely the result of mutations to genes. Although students did gain the idea that change occurs through mutation, they seem to have attached the mutagenic changes to the idea that organisms can direct that change themselves.

Freshmen gained another misconception through instruction; they significantly increased their choice of "individuals" as a response to statements about the level at which natural selection acts. The confusion among students about natural selection acting

on individuals or populations is well-documented (Andersson & Wallin, 2006; Greene, 1990; Halldén, 1988; Shtulman, 2006). Student confusion is often introduced when teachers alternate between levels of organization ranging from genes to species without distinguishing clearly between them (Andersson & Wallin, 2006). In this case, the leap from microevolutionary to macroevolutionary processes was perhaps too great for students to bridge, which has been suggested to be a common problem in evolution education (Catley, 2006). The instructional sequence we used might benefit from an additional lesson to clarify the genetic basis of variation in populations. The increased emphasis on genetics as a mechanism for variation can also help clarify the misconception of purposeful change by organisms in response to environmental pressure.

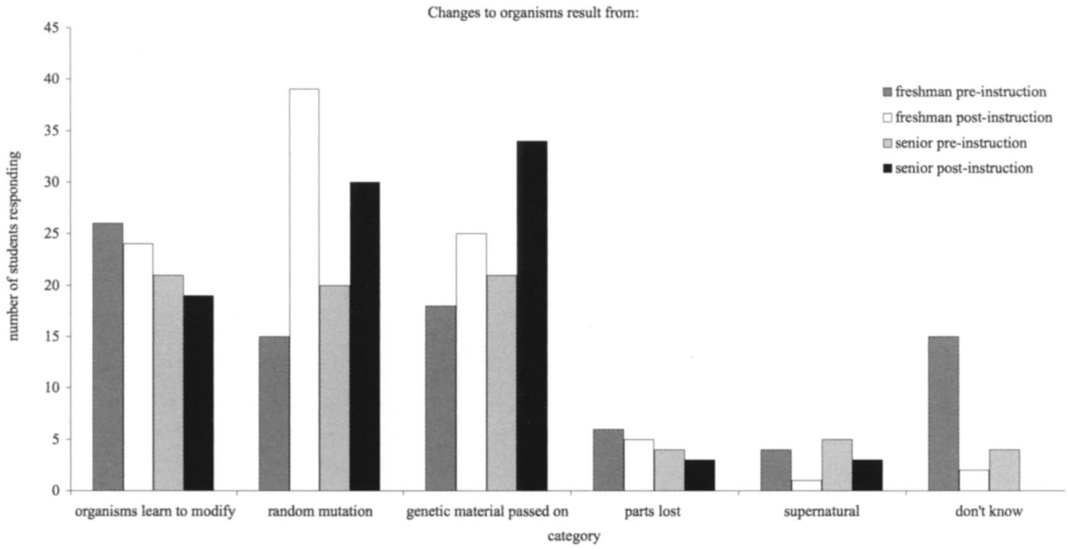

Figure 3c. Student responses to statements about mechanism of change in natural selection before and after instruction rated on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree).

Although both instructors made some modification to the lesson sequence to meet their individual needs, both freshmen and seniors significantly increased their positive response to the statement, "Natural selection is the best supported explanation for the diversity of life on Earth." For the seniors, this was the only statement for which they significantly increased their positive response. Given that the primary goal of instruction was to increase understanding about, and acceptance of, natural selection as the scientific theory that best explains diversity, this result is particularly gratifying.

We undertook this study in part to find out how our students viewed natural selection. Given the well-publicized efforts to implement non-scientific curricula (such as intelligent design) in schools, we anticipated a higher level of responses related to these ideas than we received. In the word choice portion of the survey, only one student referred to any form of non-natural intervention related to species diversity. Student responses to statements about natural selection that ascribed change to supernatural forces, or indicated natural selection did not apply to any organisms or to humans specifically were low in both groups. For our students in Hawaii, at least, this result implies that students are ready to accept natural selection, and that suggestions to "teach the controversy" might be counterproductive by introducing a non-scientific idea that is not necessarily already present in the students' worldview.●

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Appendix A. Survey

Write down the first three words you think of for natural selection.

Circle all answers you think are accurate about each statement.

Natural selection applies to ...

individuals	populations	everything but humans	all organisms	nothing	I don't know

The measure of success in nature is ...

age reached	enemies killed	mating opportunities	surviving offspring	food gathered	I don't know

Changes result from ...

organisms learn to modify their bodies	random mutation	genetic material is passed on	loss of body parts	supernatural intervention	I don't know

Choose the response that best represents how you feel about each statement.

Natural selection is the best supported explanation for the diversity of life on Earth.

strongly disagree	disagree	unsure	agree	strongly agree
1	2	3	4	5

Natural selection helps explain why organisms look the way they do.

strongly disagree	disagree	unsure	agree	strongly agree
1	2	3	4	5

Natural selection applies to all organisms on Earth.

strongly disagree	disagree	unsure	agree	strongly agree
1	2	3	4	5

Natural selection affects humans.

strongly disagree	disagree	unsure	agree	strongly agree
1	2	3	4	5

Scientists need to consider natural selection when trying to solve problems.

strongly disagree	disagree	unsure	agree	agree
1	2	3	4	5

BIO

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